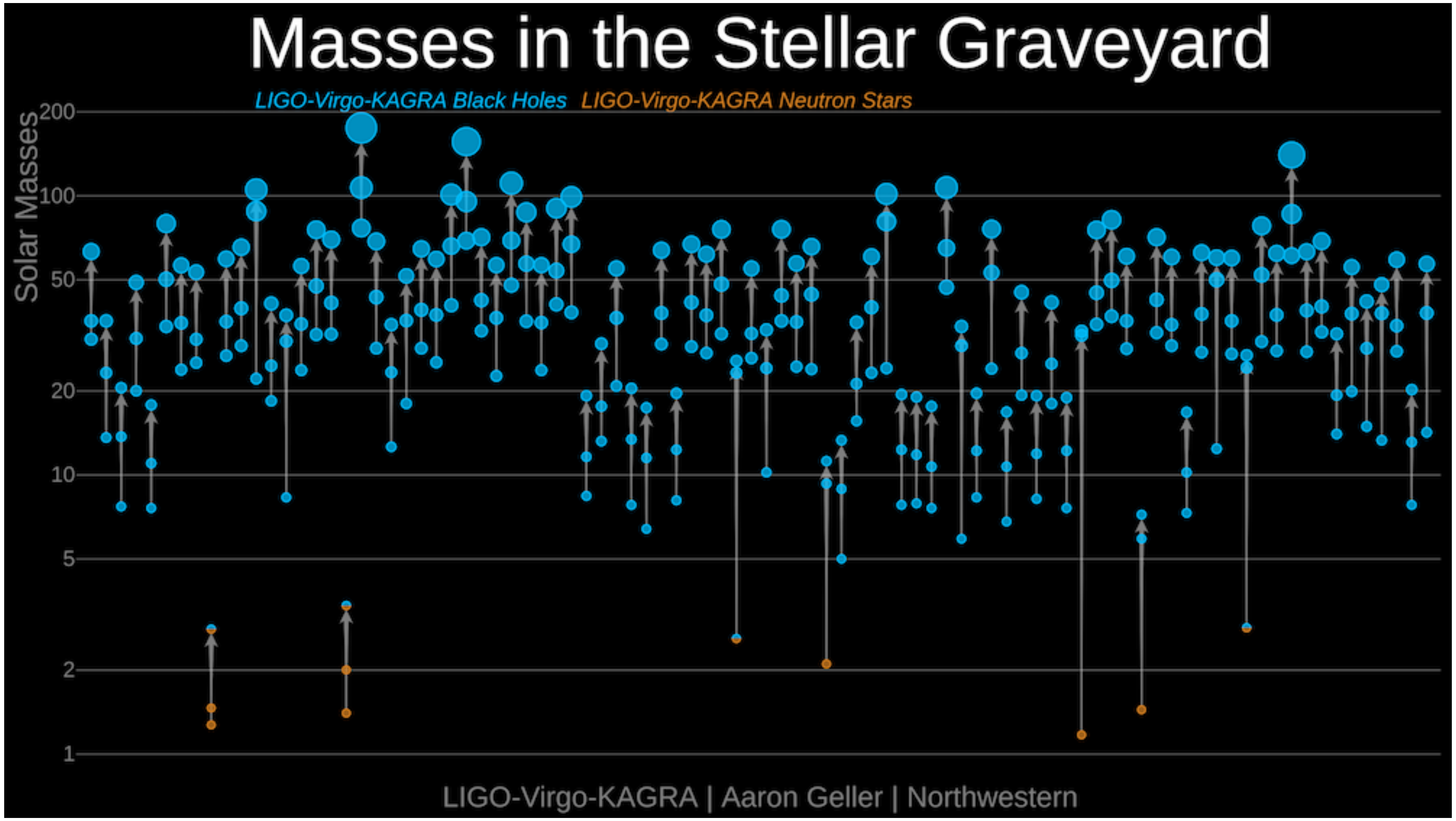
Black holes in scalar field

Taishi Ikeda
(Sapienza University of Roma)

- *Phys.Rev.D* 103 (2021) 2, 024020. T.I, L.Bernard, V.Cardoso, M.Zilhao
- arXiv2207(?).XXXX V.Cardoso,TI, R.Vicente M.Zilhao

Many black holes

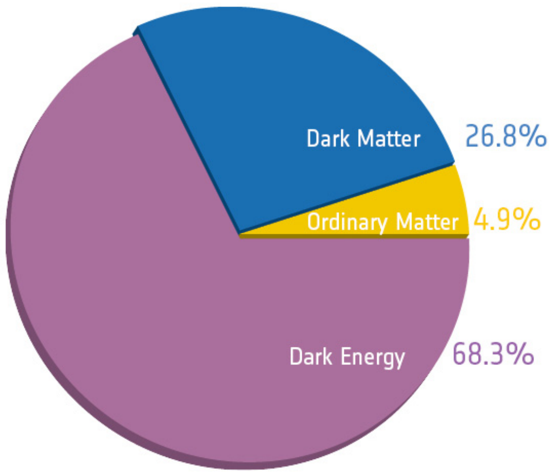


From O3B catalog

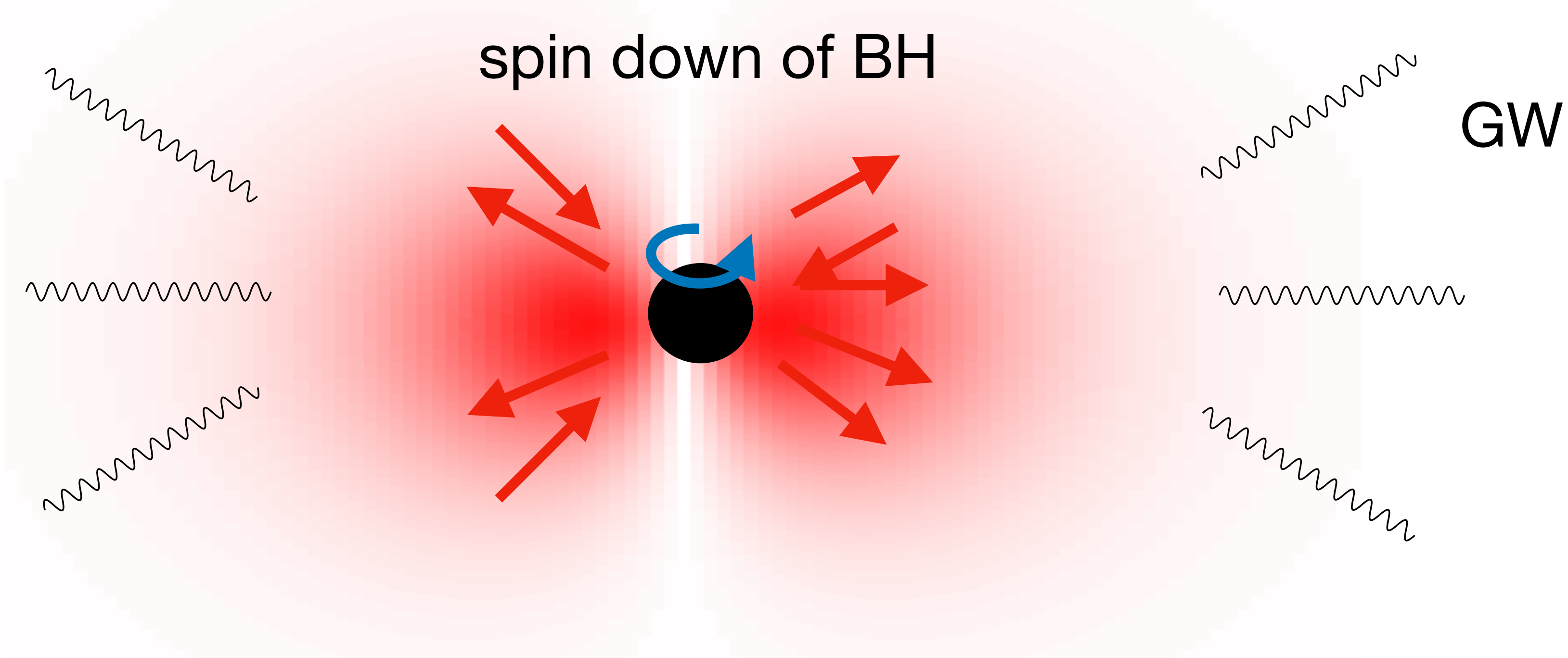
- BHs give us hints of ….
  - Origin of black holes/ binaries, primordial black hole, early universe, a particle detector, test of gravitational theory, et al

BHs as particle detector

- New physics predicts light fields.
  - axion, axion-like particle ? see. Arvanitaki et.al (2015)
  - light vector field, dark photon ?
  - light tensor field ? cf:. massive gravity, bigravity
- BHs are useful tools for searching new particles.
  - Superradiant instability see also Richard's talk

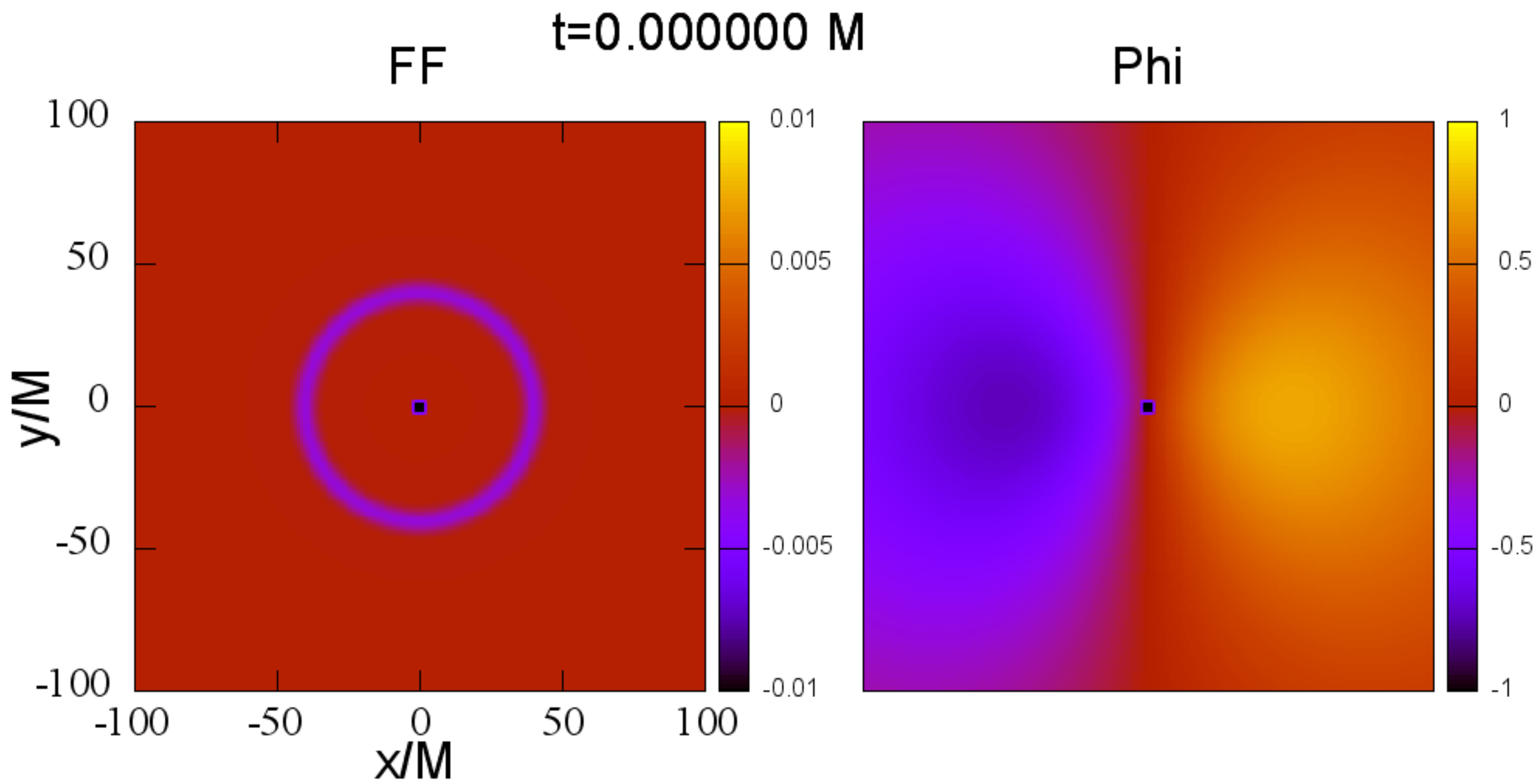


$$\tau \sim 100\tilde{a}\left(\frac{10^6 M_\odot}{M}\right)^8\left(\frac{10^{-16}\mathrm{eV}}{\mu}\right)^9 \mathrm{sec}$$



BHs as particle detector

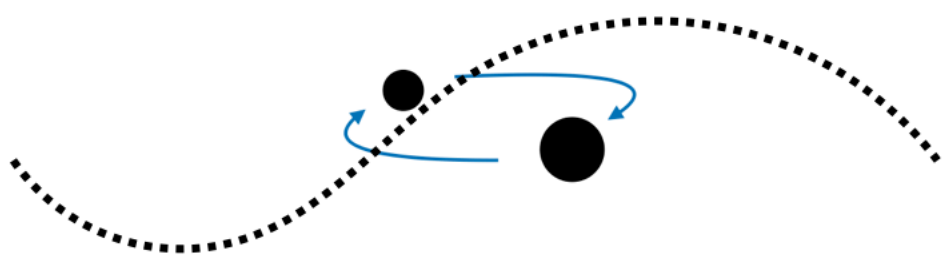
$$\begin{cases} (\nabla^2 - \mu^2)\Phi = \dfrac{k_{\rm a}}{2}\tilde{F}_{\mu\nu}F^{\mu\nu} \\ \nabla_\mu F^{\mu\nu} = 2k_{\rm a}\tilde{F}_{\nu\mu}\nabla^\mu\Phi \end{cases}$$



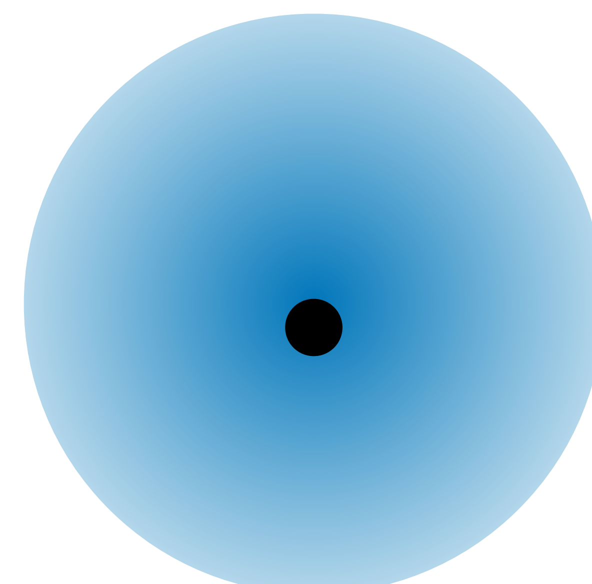
Phys.Rev.D 99 (2019) M.Boskovic et al
Phys.Rev.Lett. 122 (2019) 8, 081101 T.I et al

Black hole physics

- We can imagine several situations in which BHs interact with light field as an environment.

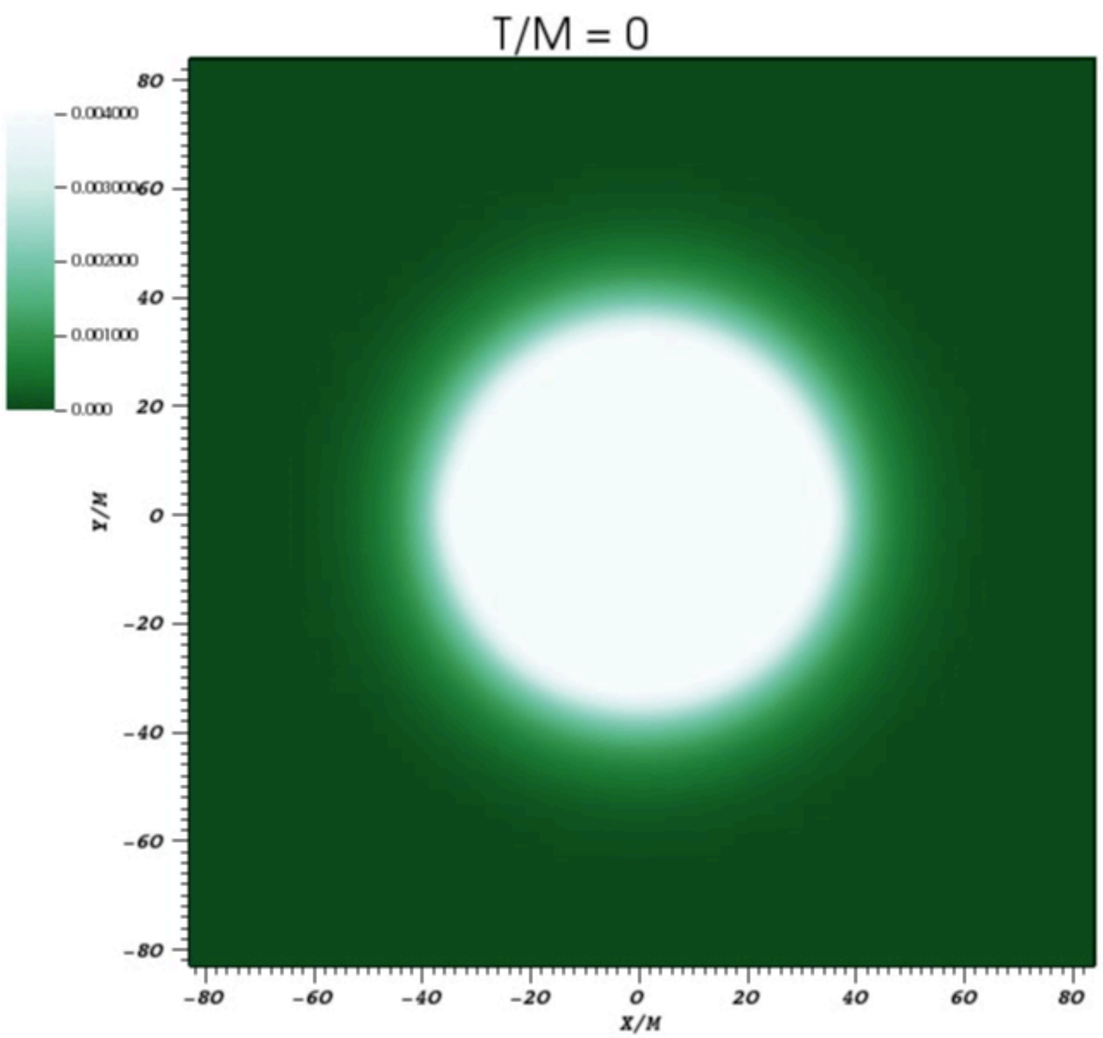


Binary black hole in scalar field
What is typical state ?



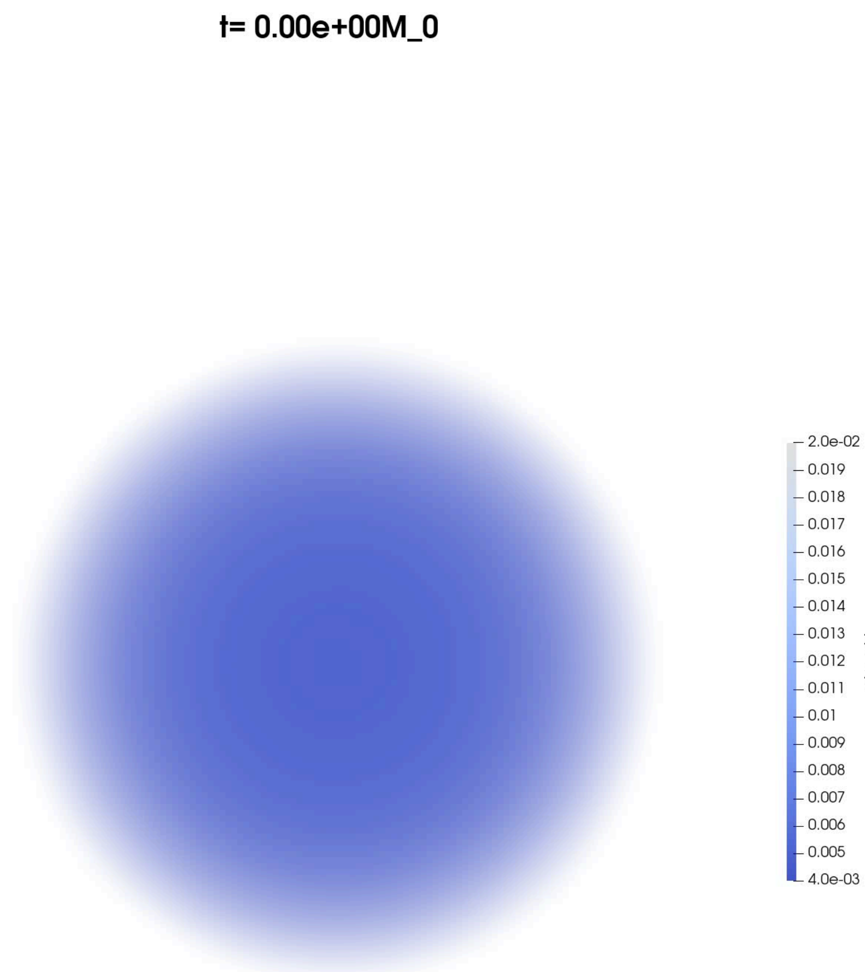
Black hole in dark matter halo
accretion of BS by BH ?
but what is the process, and time scale ?

Gravitational molecule



Phys.Rev.D 103 (2021) 2, 024020. T.I. et al
also James's talk

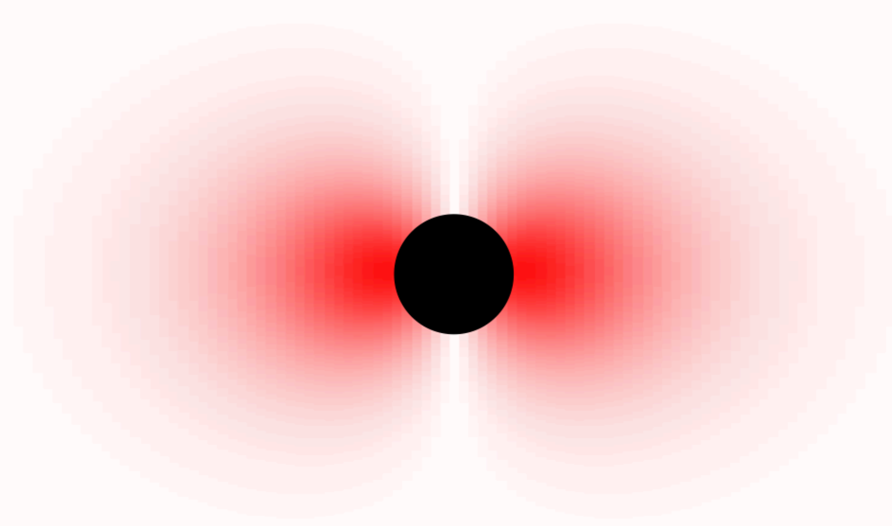
Accreting large BS into BH



appear soon with V.Cardoso, R.Vicente, M.Zilhao

Gravitational molecule

Gravitatioanl atom

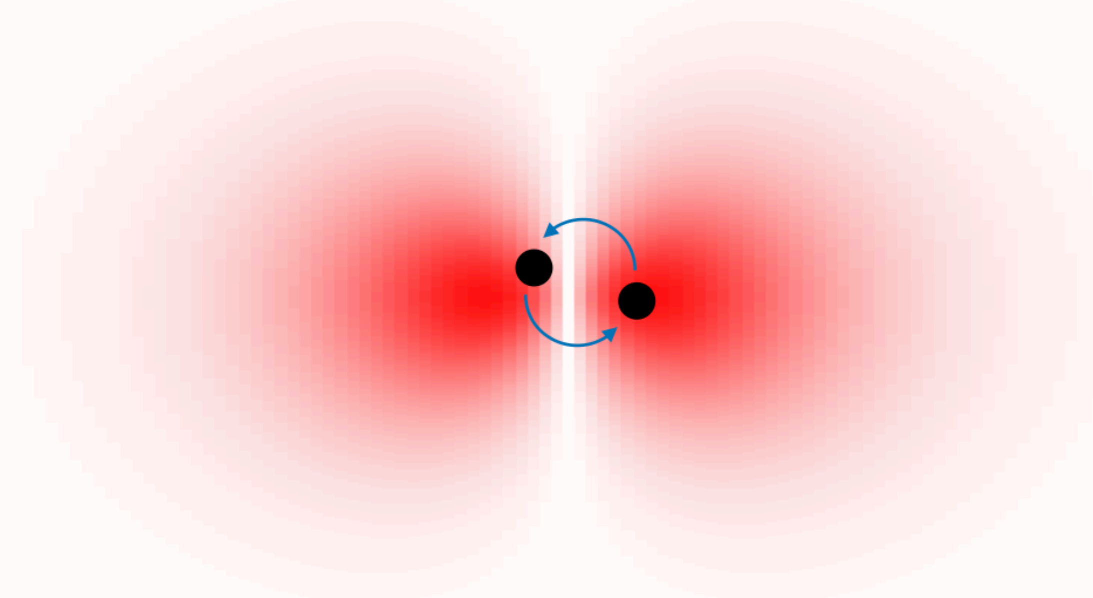


$$i\partial_t\varphi = \left(-\frac{1}{2\mu^2}\nabla^2 + V(r)\right)\varphi$$

$$V(r) = \frac{\mu M}{r}$$

Hydrogen atom

Gravitatioanl molecule



$$i\partial_t\varphi = \left(-\frac{1}{2\mu^2}\nabla^2 + V(r)\right)\varphi$$

$$V(r) = \frac{\mu M_1}{|r - r_1(t)|} + \frac{\mu M_2}{|r - r_2(t)|}$$

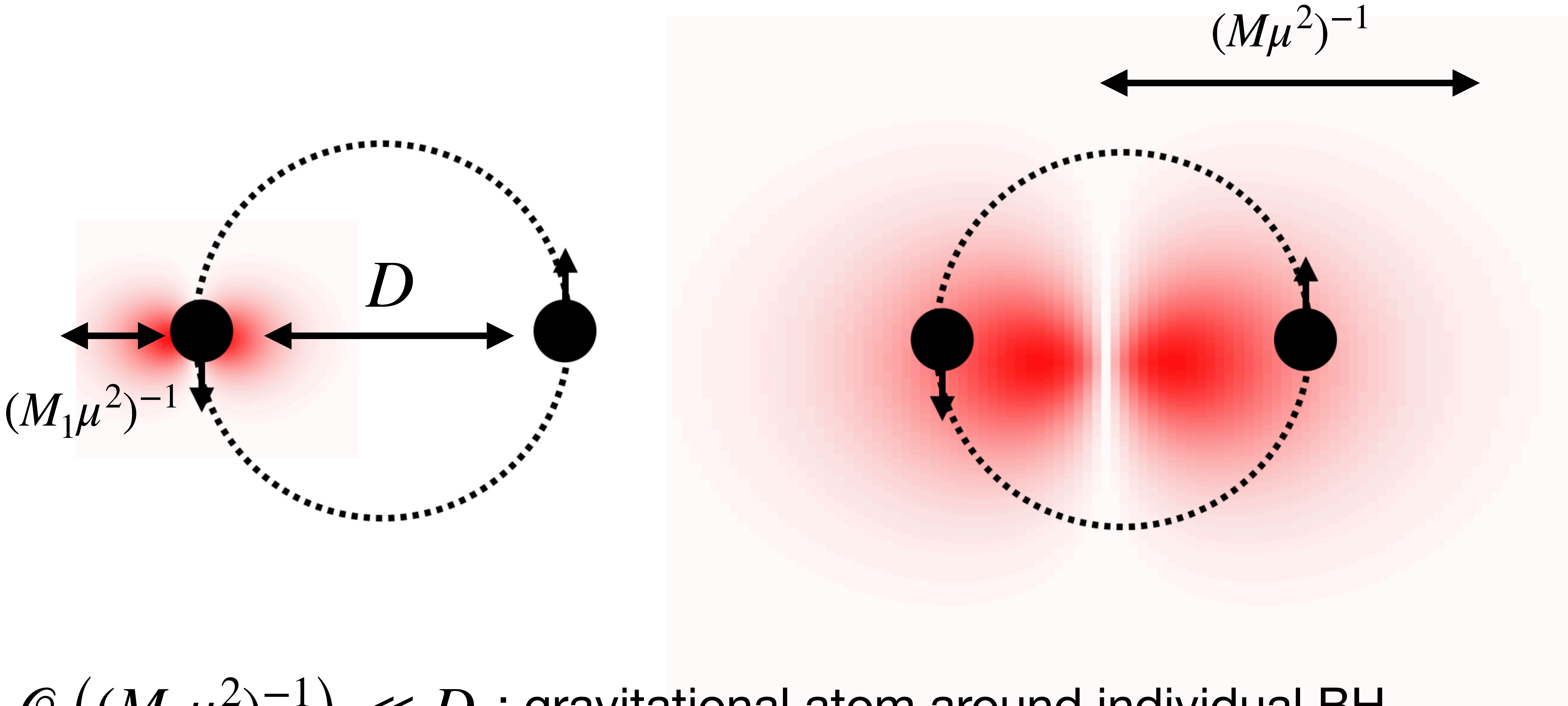
Di-hydrogen molecule

→ spectrum of molecule

Typical length scale

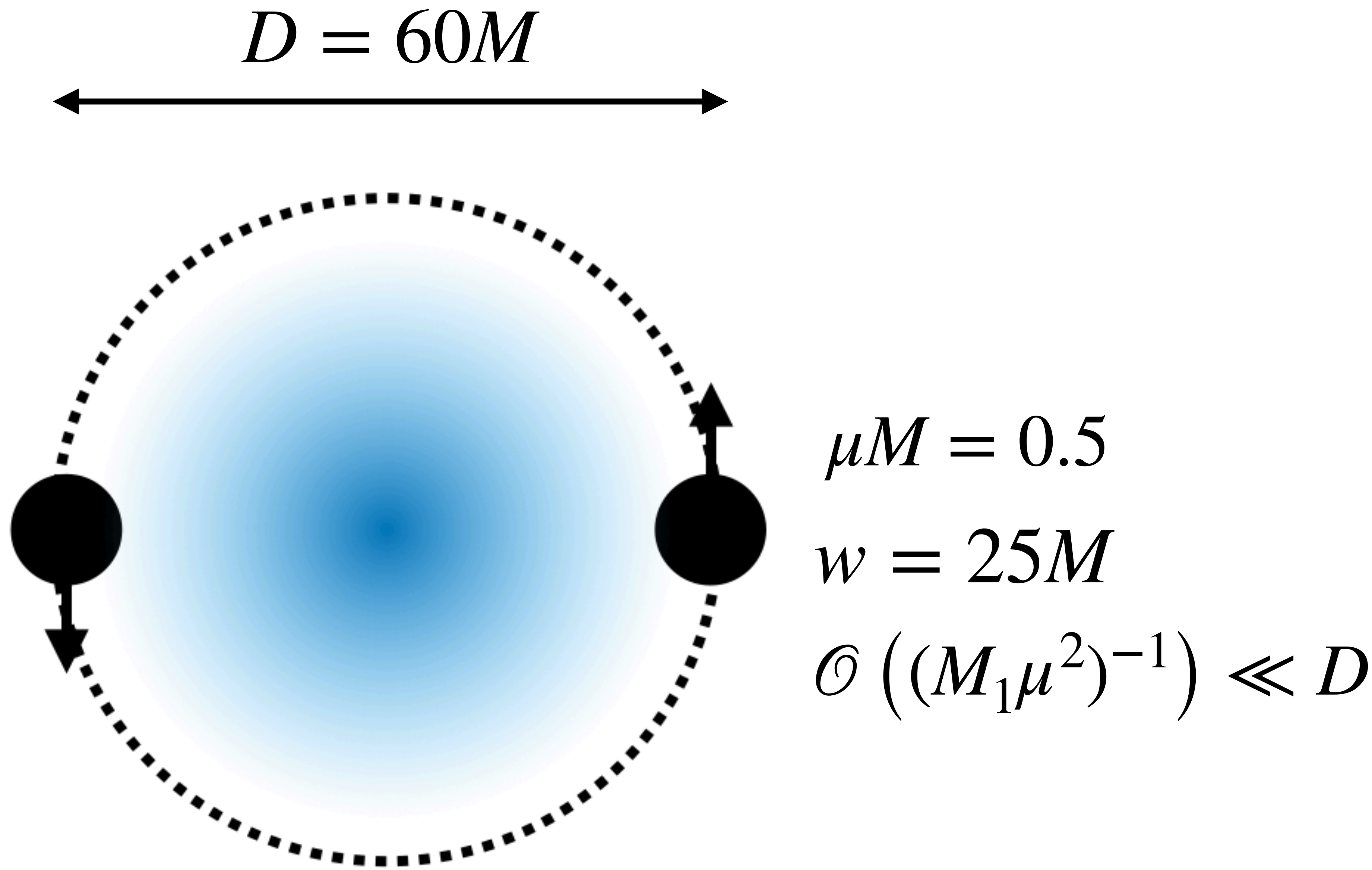
$$\left(\Box - \mu^2\right)\phi = 0$$

$$M_1 = M_2 = \frac{M}{2}$$



$\mathcal{O}\left((M_1\mu^2)^{-1}\right) \ll D$: gravitational atom around individual BH

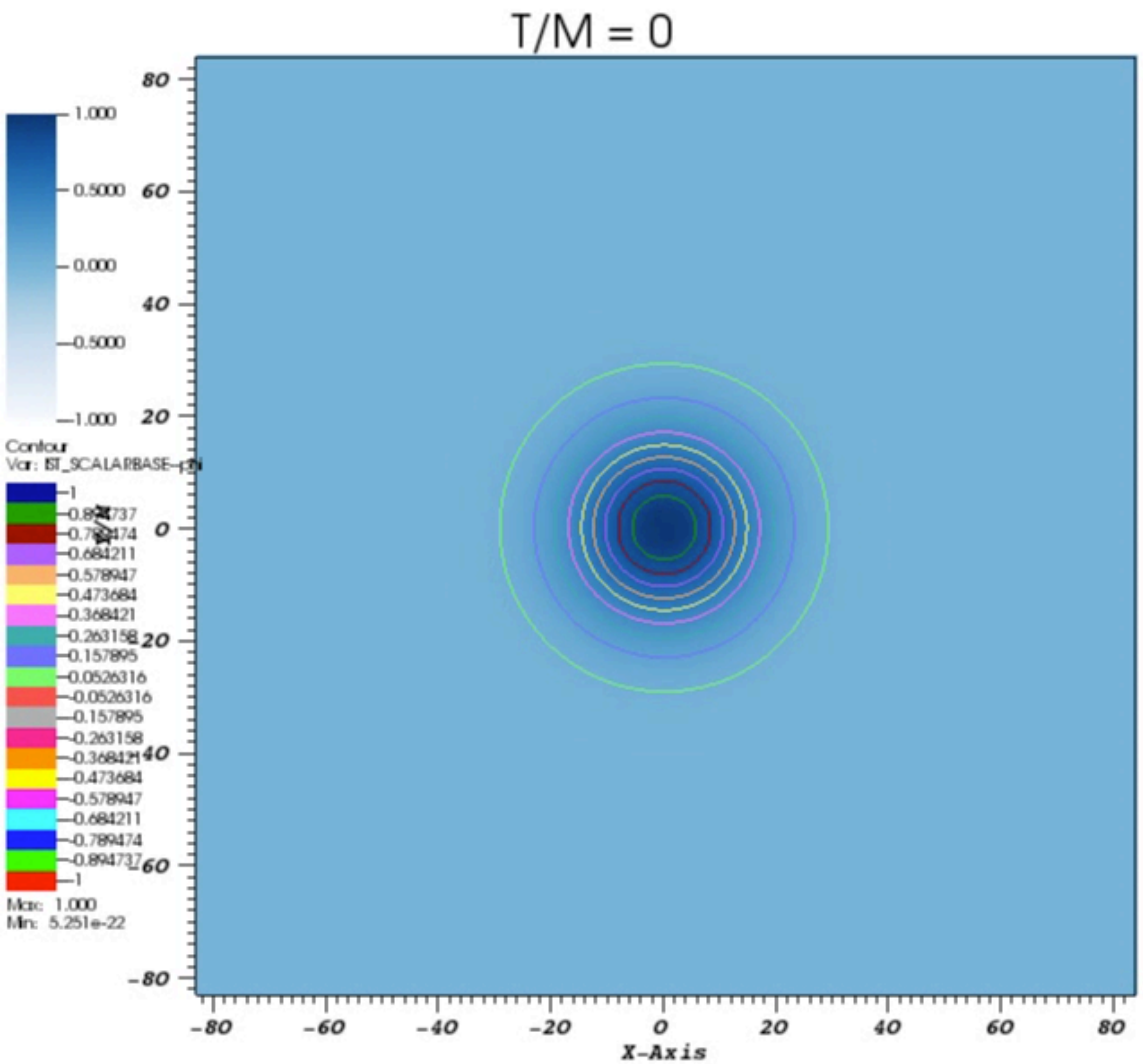
$\mathcal{O}\left((M\mu^2)^{-1}\right) \gtrsim D$: gravitational molecule around BH binary



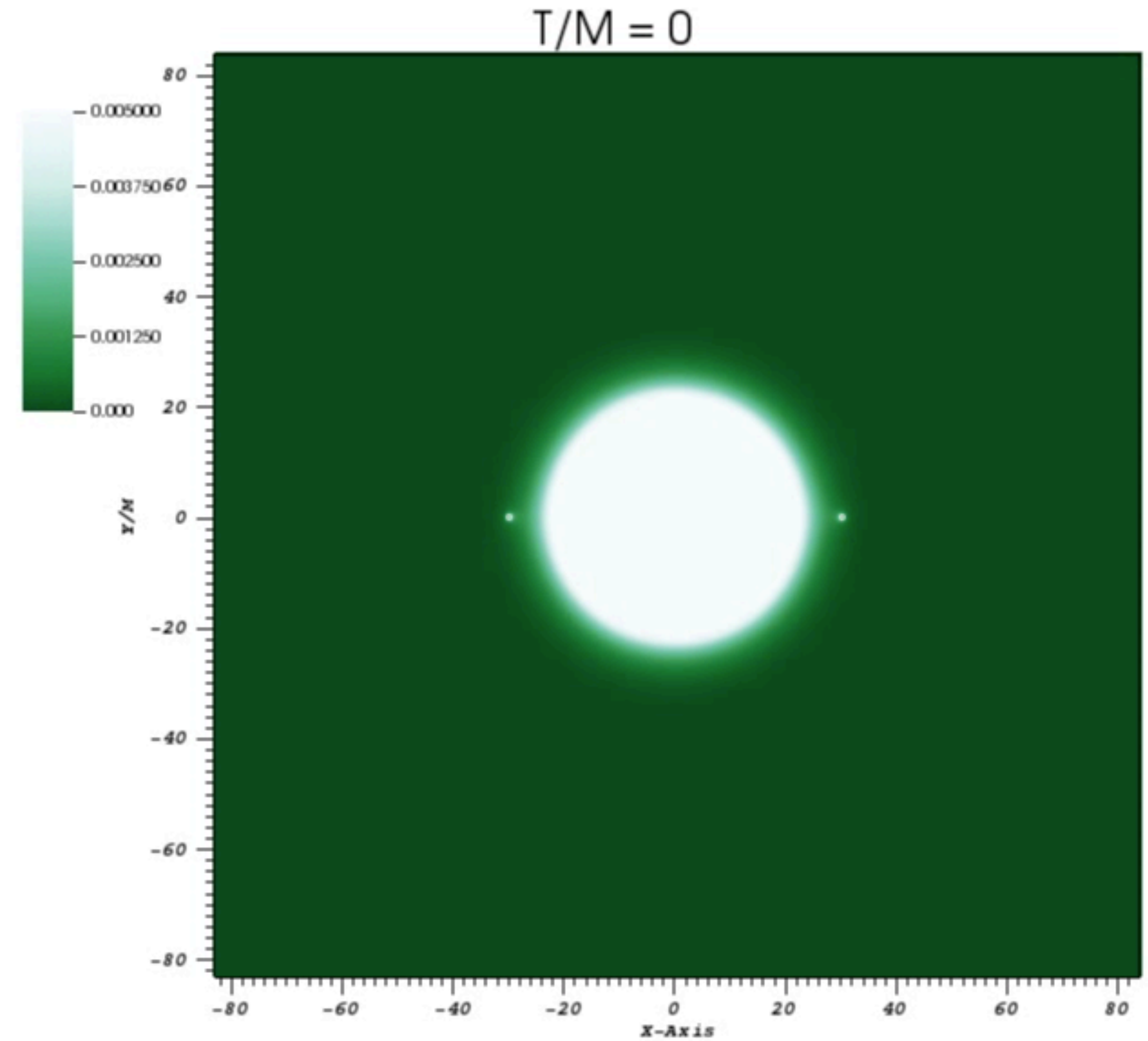
Simulation 1 : Gaussian initial data

Simulation 1

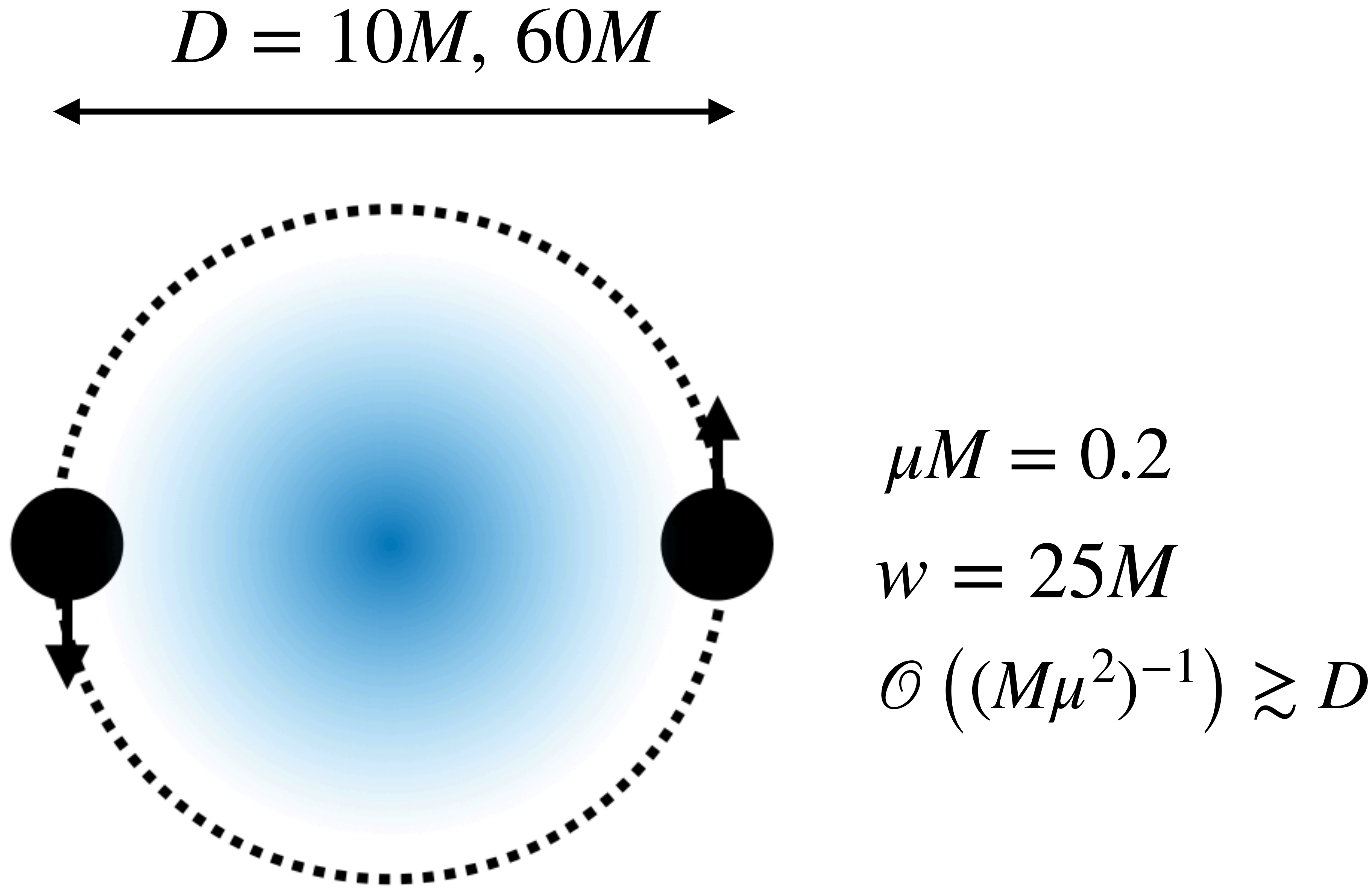
Scalar field



Energy density



- Gravitational atom around individual BHs.

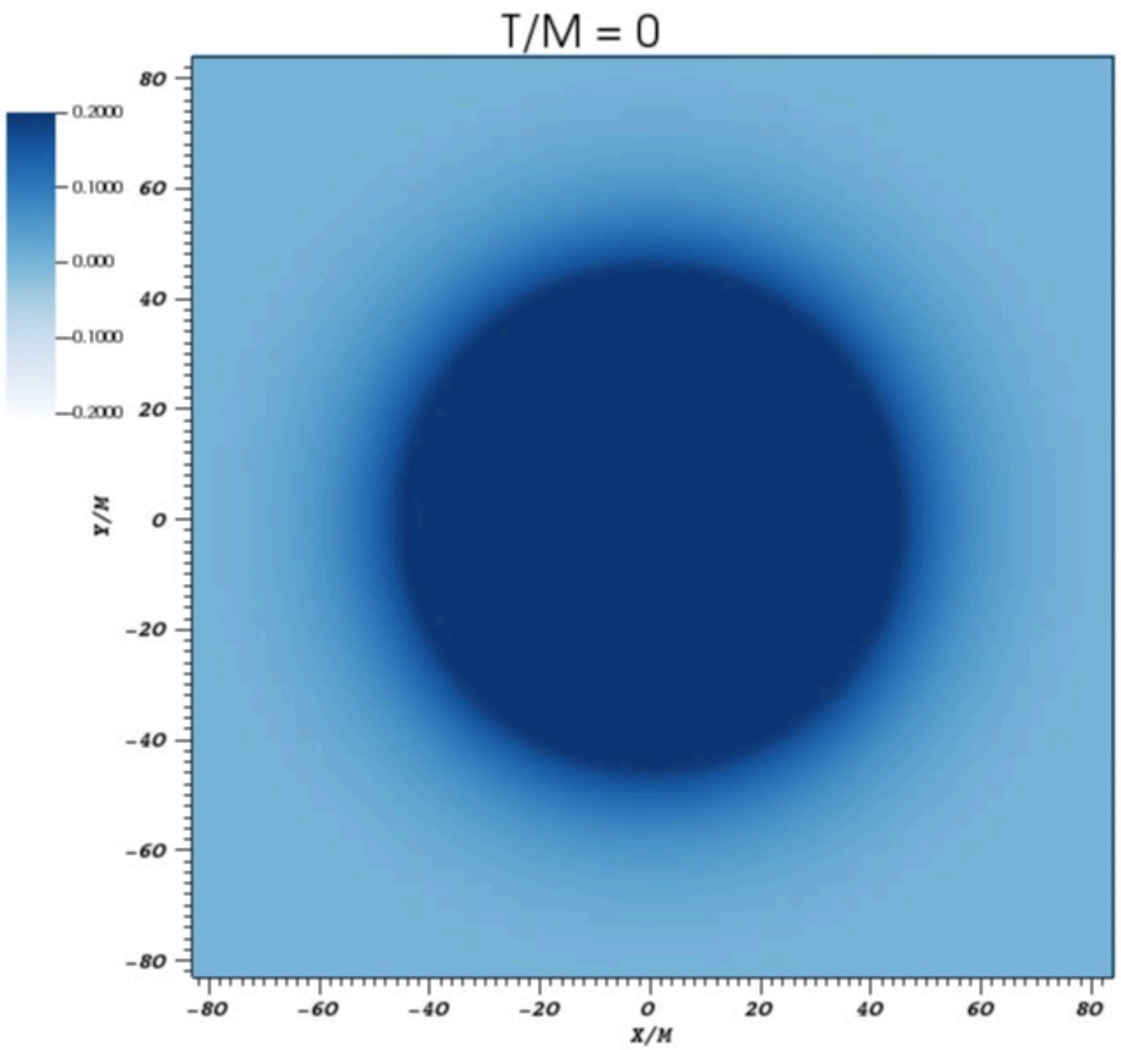


Simulation 2 : Gaussian initial data

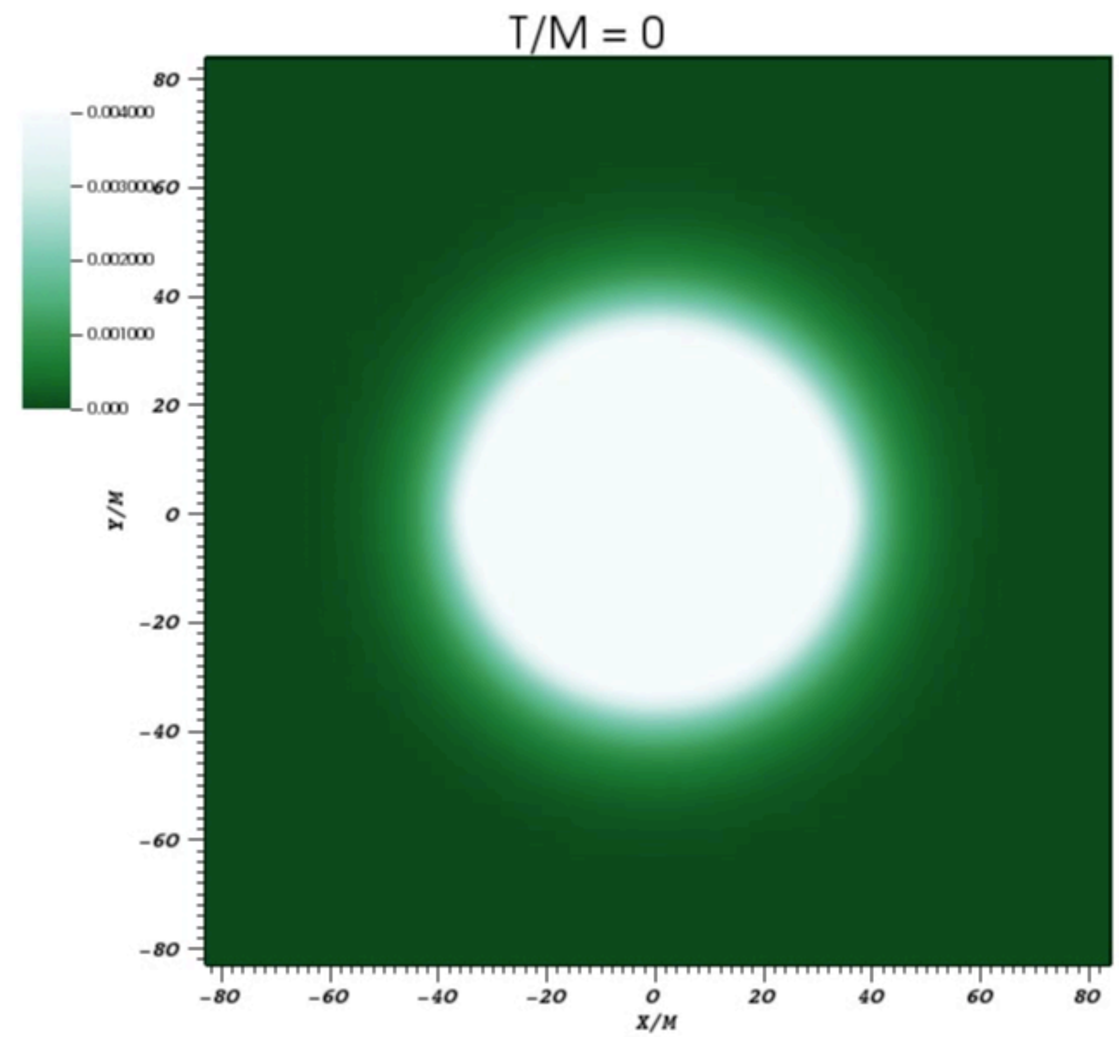
Simulation 2

$D = 60M$

Scalar field

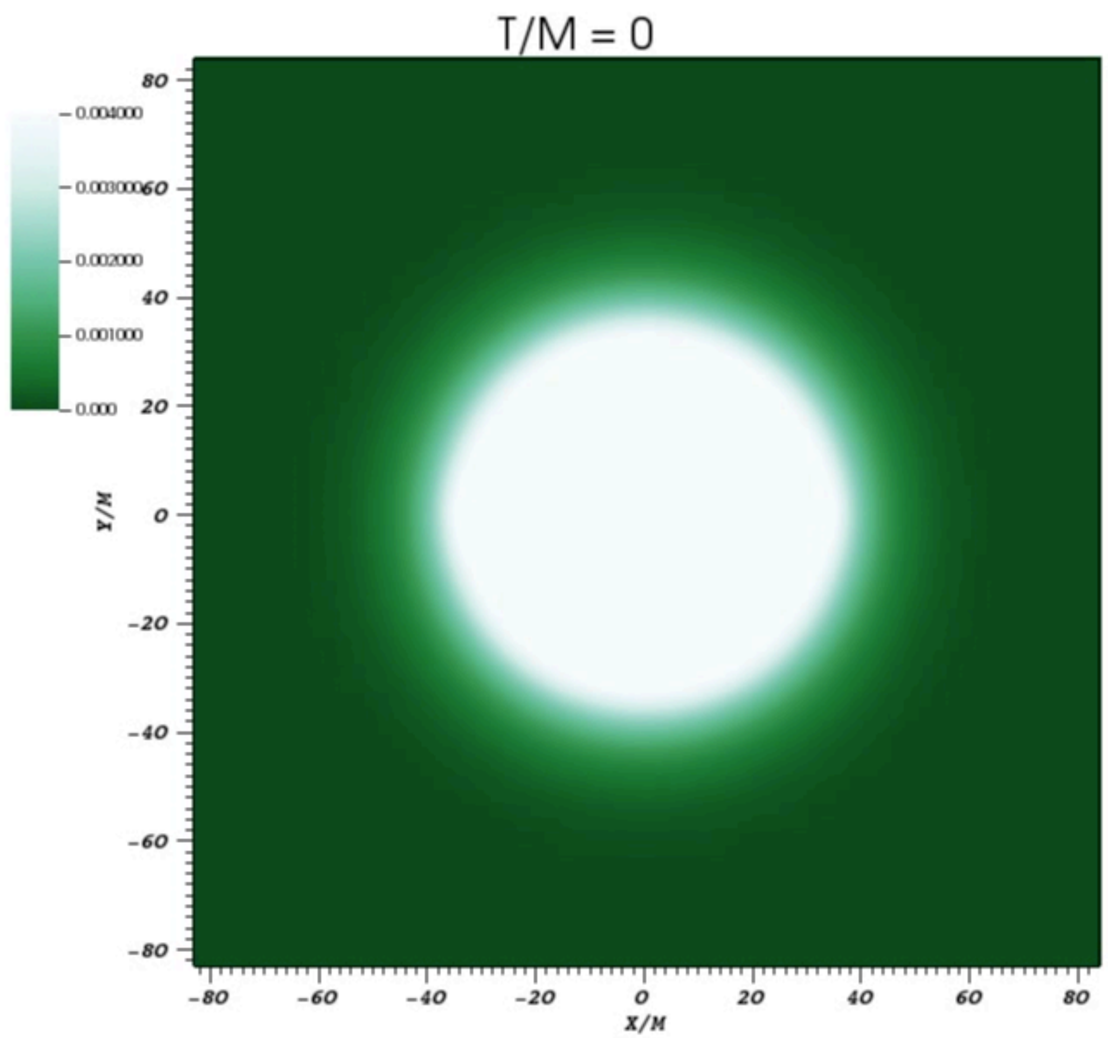


Energy density



- “Monopole” gravitational molecule around BH binary.
- We checked the spectrum is similar to Di-hyrogen molecule.

Gravitational molecule



Phys.Rev.D 103 (2021) 2, 024020. T.I. et al
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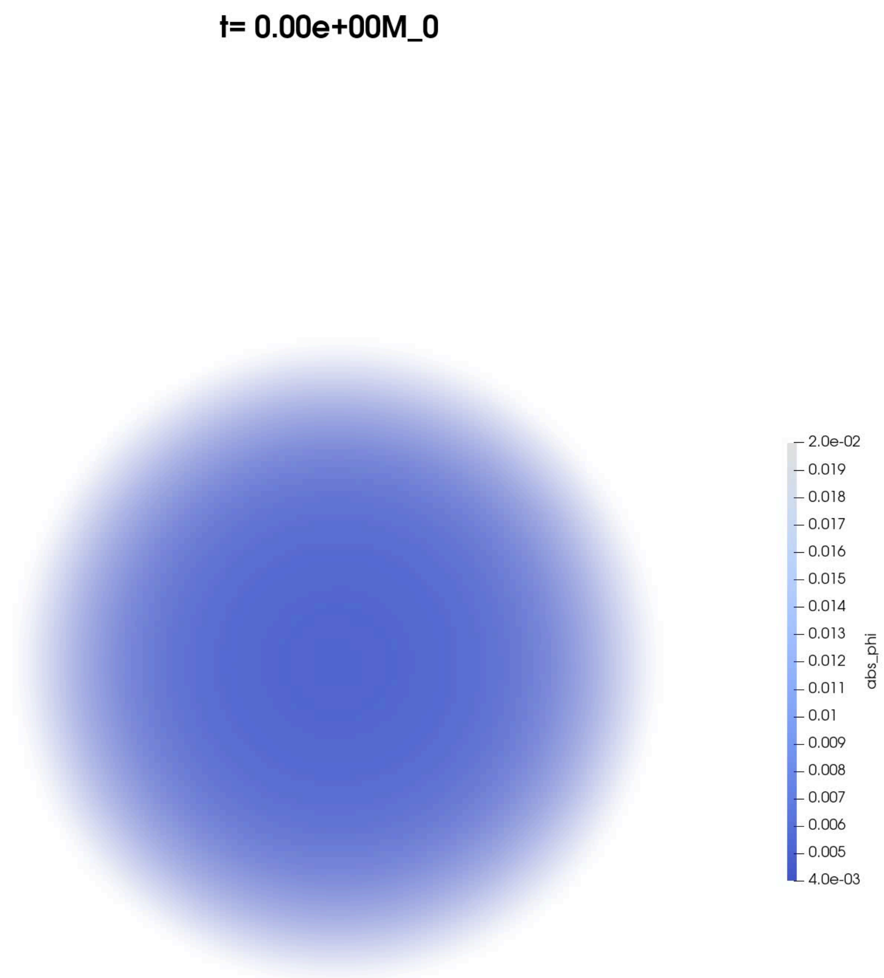


appear soon

BS as dark matter

- Fuzzy dark matter : light scalar field

$$S = \int d^4x \sqrt{-g}\left(\frac{R}{16\pi} - g^{\mu\nu}\nabla_\mu\psi\nabla_\nu\psi^* - \mu^2|\psi|^2\right)$$

$$\frac{M_{\rm BS}}{M_\odot} = 9\times 10^9 \frac{100\mathrm{pc}}{R_{\rm BS}}\left(\frac{10^{-22}\ \mathrm{eV}}{\mu}\right)^2$$

BS appears at the center of DM halo.

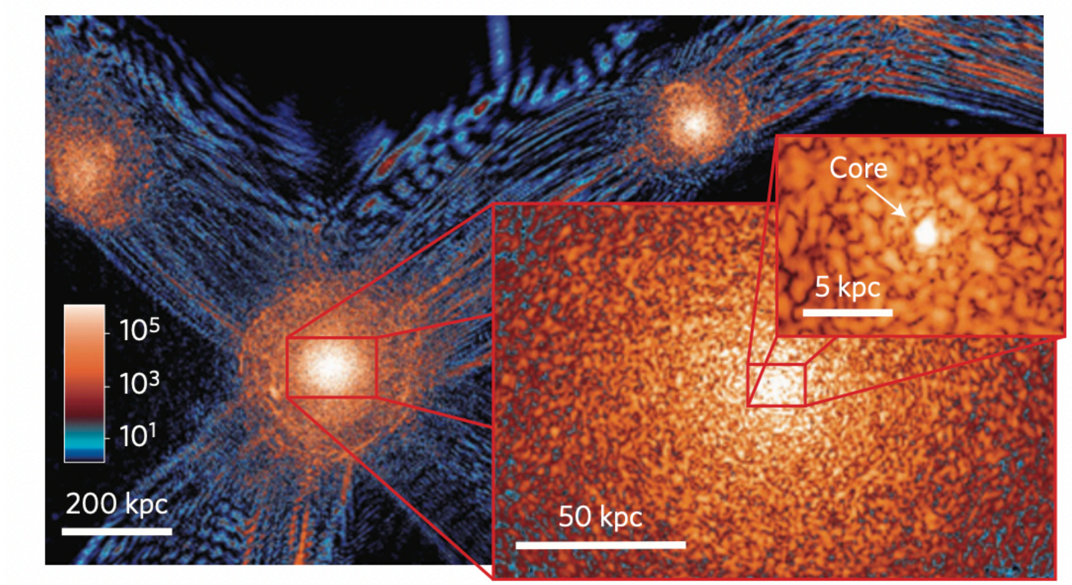


Figure 2 | A slice of the density field of the ψDM simulation on various scales at $z = 0.1$. This scaled sequence (each of thickness 60 pc) shows how quantum interference patterns can be clearly seen everywhere from

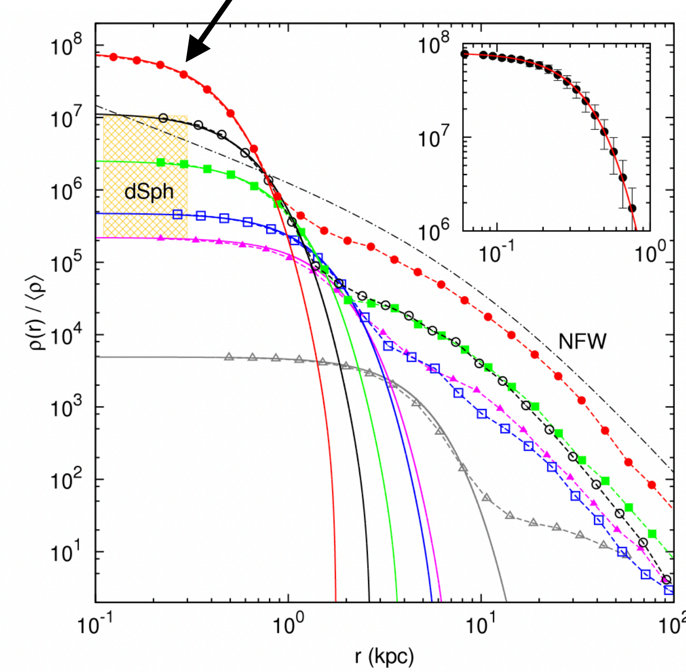
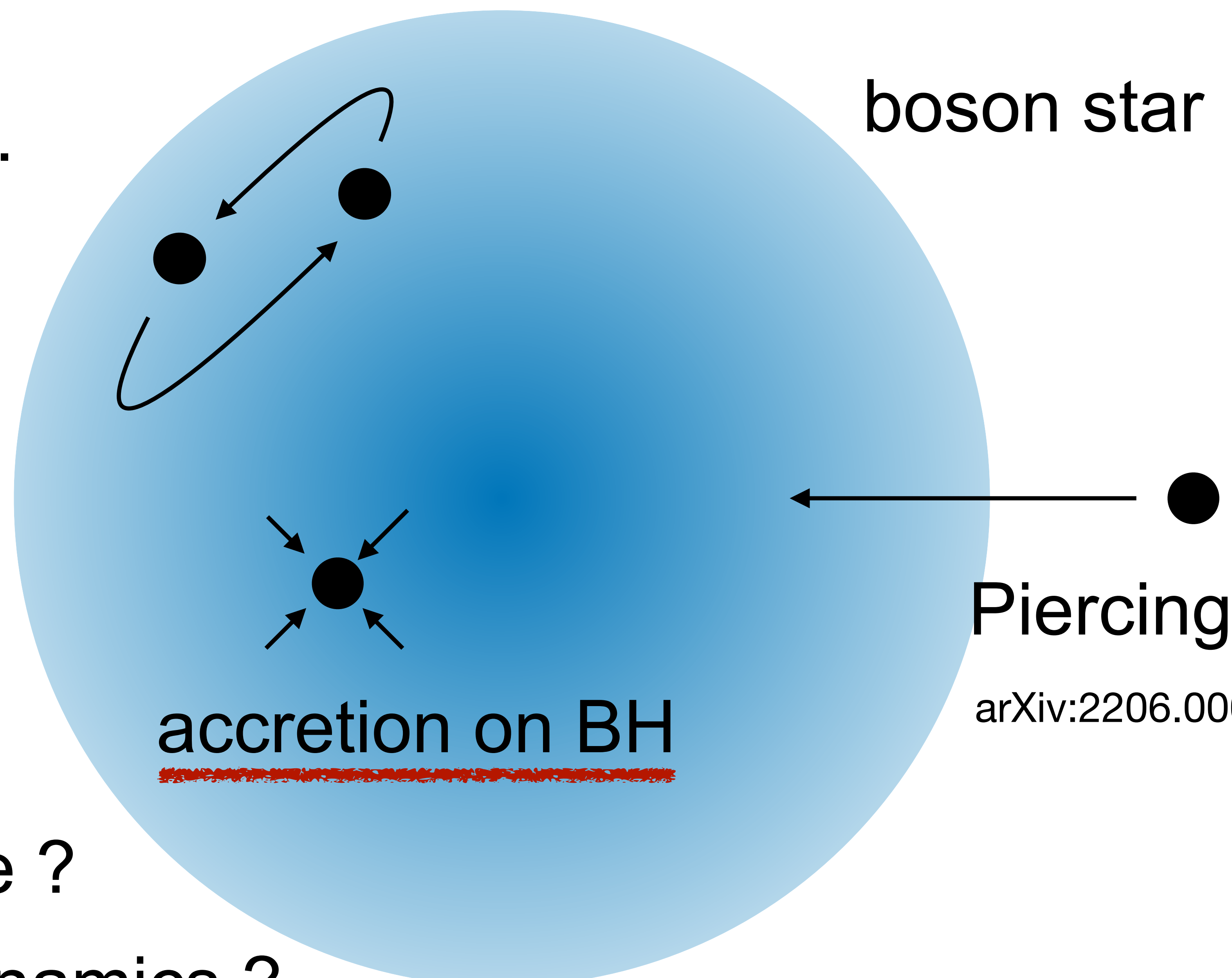


Figure 3: Radial density profiles of haloes formed in the ψDM model. Dashed lines with various sym-

Schive et.at.(2014))

Possible interactions with BHs

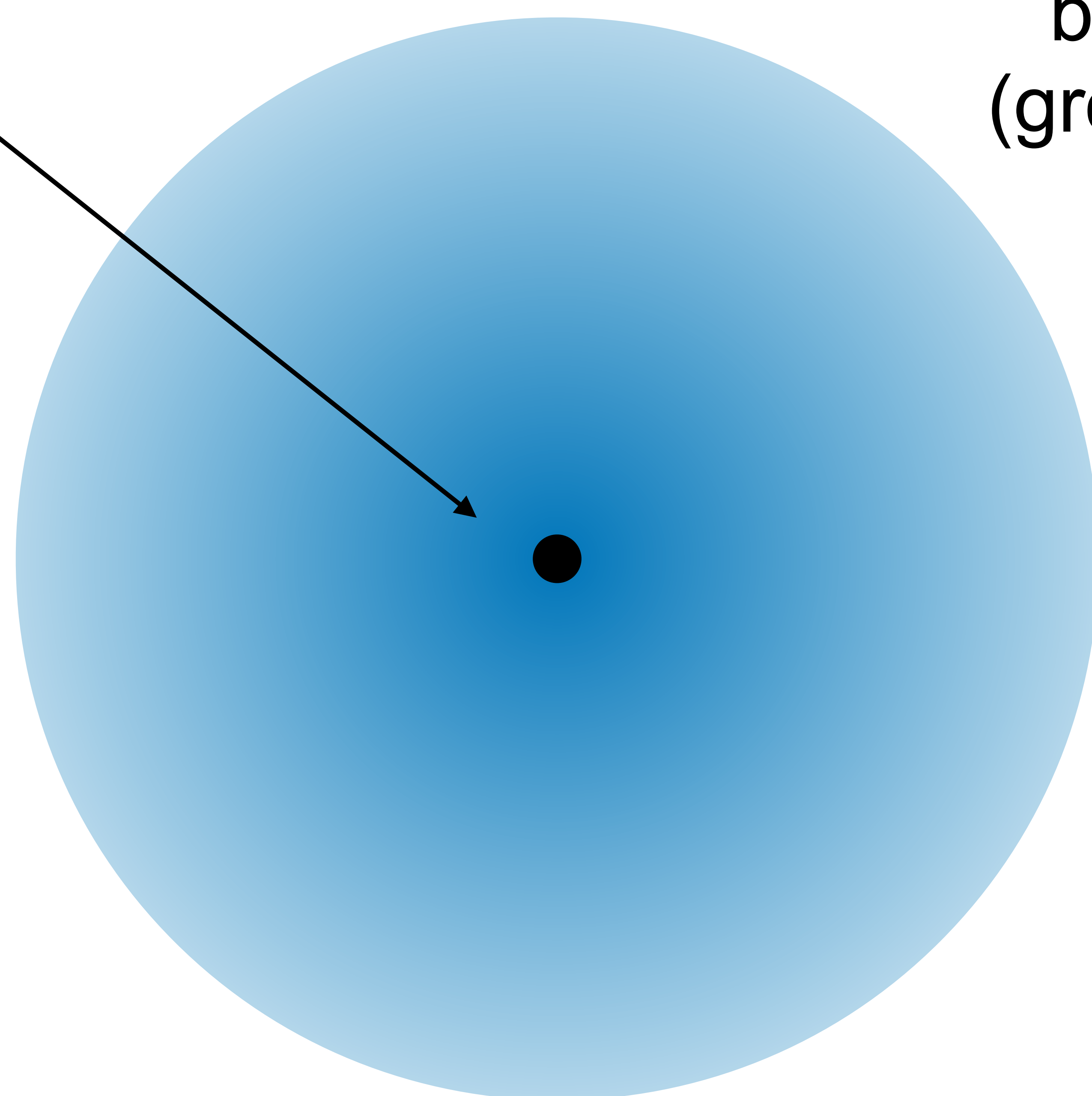


- Time scale ?
- Typical dynamics ?

Set up

Black hole (M_0)

boson star
(ground state)



Parameters

$(M_{\mathrm{BS}}/M_0, R_{\mathrm{BS}}/M_0)$

Initial Data

Relevant physics

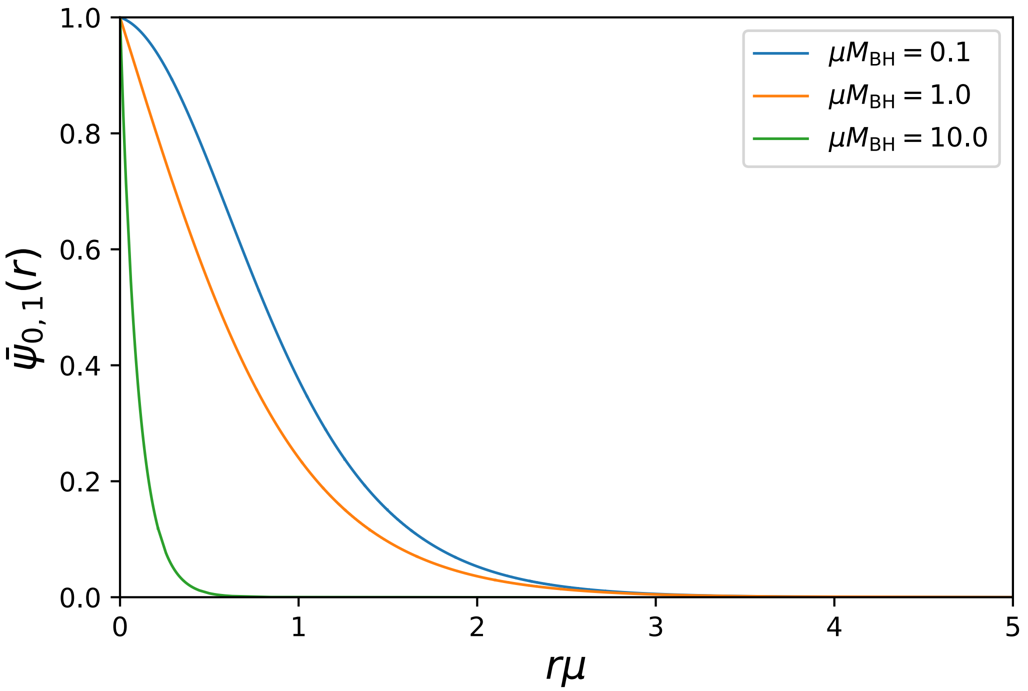
- boson star normal mode   Annulli et al (2020)

$$\omega_{\rm NM} = \kappa M_{\rm NBS}^2 \mu^3 \qquad \kappa = \mathcal{O}(0.1)$$

- Schrodinger-Possion eq.

$$\begin{cases} i\dfrac{\partial \Psi}{\partial t} = -\dfrac{1}{2\mu}\Delta\Psi + \mu\Phi_N\Psi \\ \Delta\Phi_N = 4\pi\mu\,|\Psi|^2 \end{cases}$$

with $\Phi_N = -\dfrac{M_0}{r} + \delta\Phi_N$



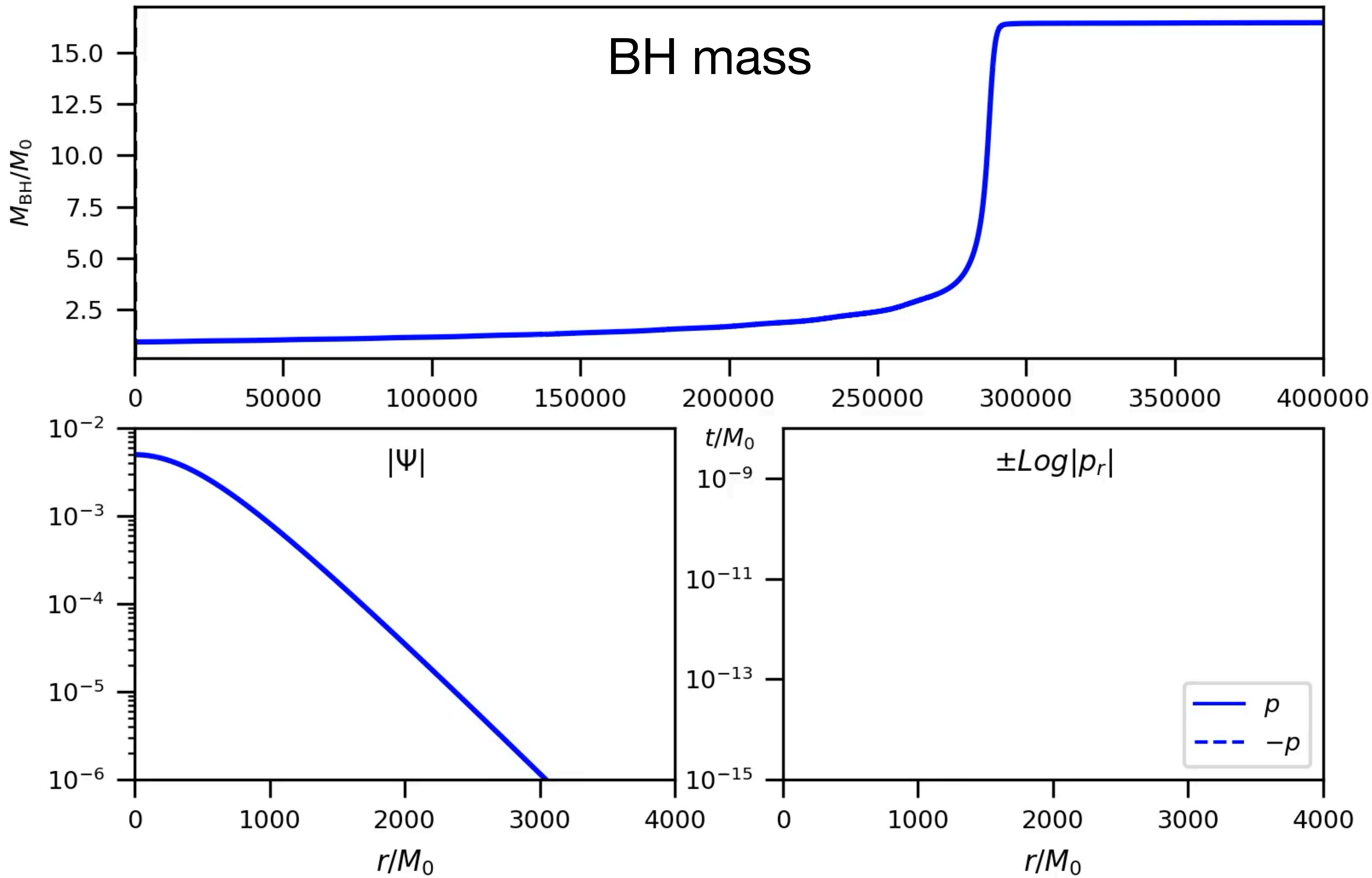
scaling symmetry : $(r, \Psi_0, \delta\Phi_N, \Omega, M) \to (\lambda^{-1}r, \lambda^2\Psi_0, \lambda^2\delta\Phi_N, \lambda^2\Omega, \lambda M)$

- Gravitational atom

Numerical result

$R_{\rm BS} = 1360 M_{\rm BH,0}$

$M_{\rm BS} = 15.5 M_{\rm BH,0}$



Scalar field

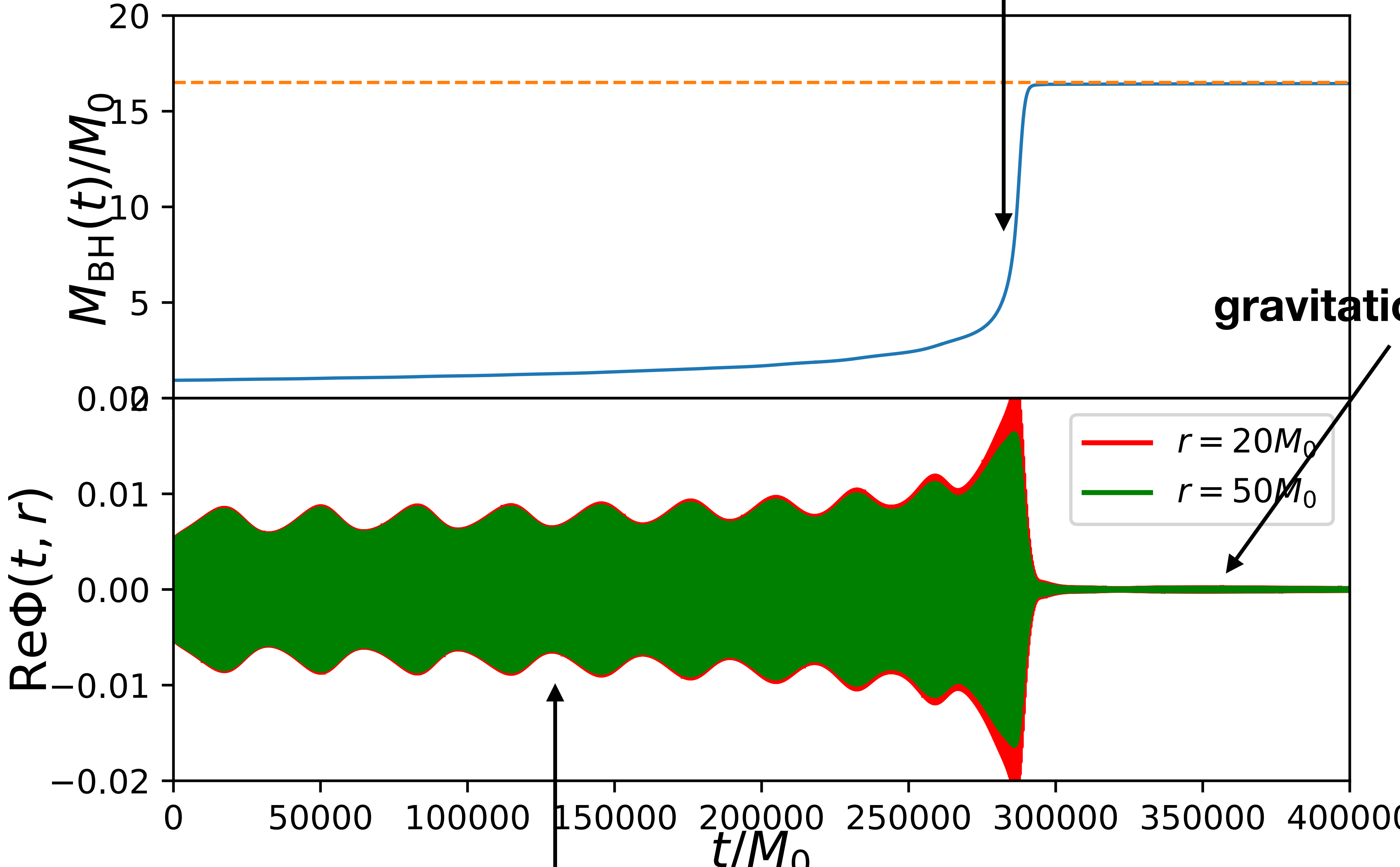
Energy flux

Numerical result

Potential barrier vanishes for larger BH.
$M_{\rm BH,crit} = 0.25\mu^{-1}$

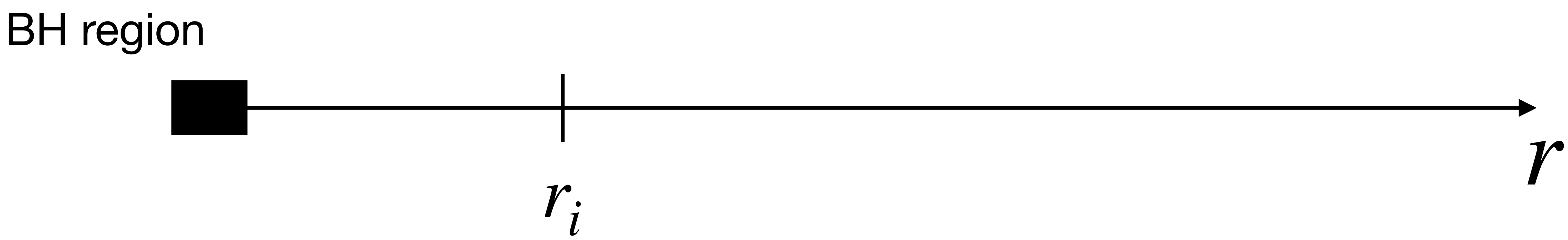
catastrophic stage

gravitational atom



BS normal mode (boson-quake)

toy model for first phase



$U_{\rm BH} \gg U_{\rm BS}$ $\qquad$ $U_{\rm BH} \ll U_{\rm BS}$

- Test field approximation

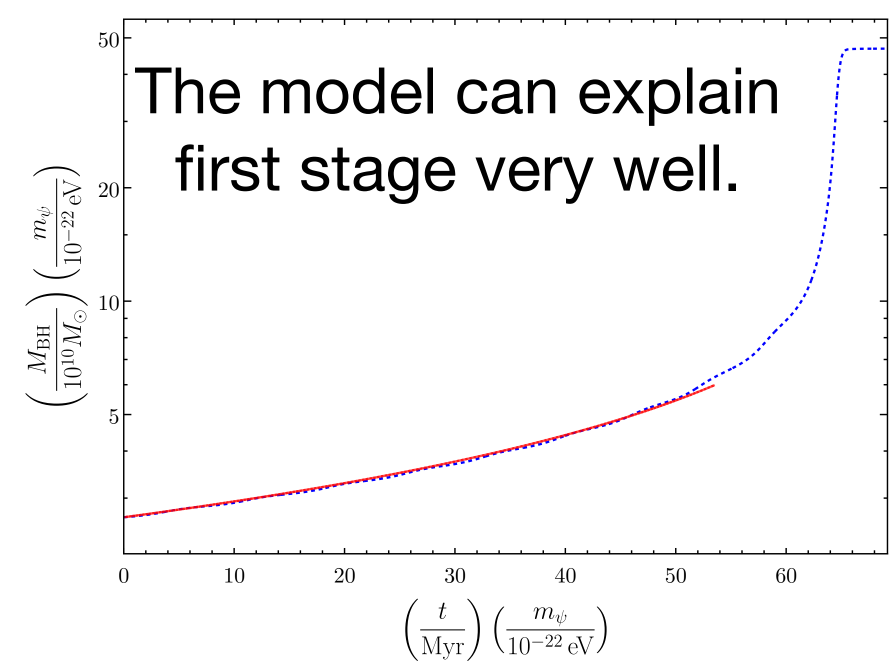
$$\psi \sim \frac{T}{2M} e^{-i\omega\left\{t + 2M\log\left(1 - \frac{r}{2M}\right)\right\}}$$

- Schrodinger-Poisson eq.

$$\psi \sim \mu^2 M_{\rm BS}^2 \left(1 + \frac{3M}{M_{\rm BS}}\right) e^{-i\omega t} \qquad r \sim \frac{R_{\rm BS}}{M_{\rm BS}} M$$

- match at $r \sim r_i$
- the energy flux into BH horizon

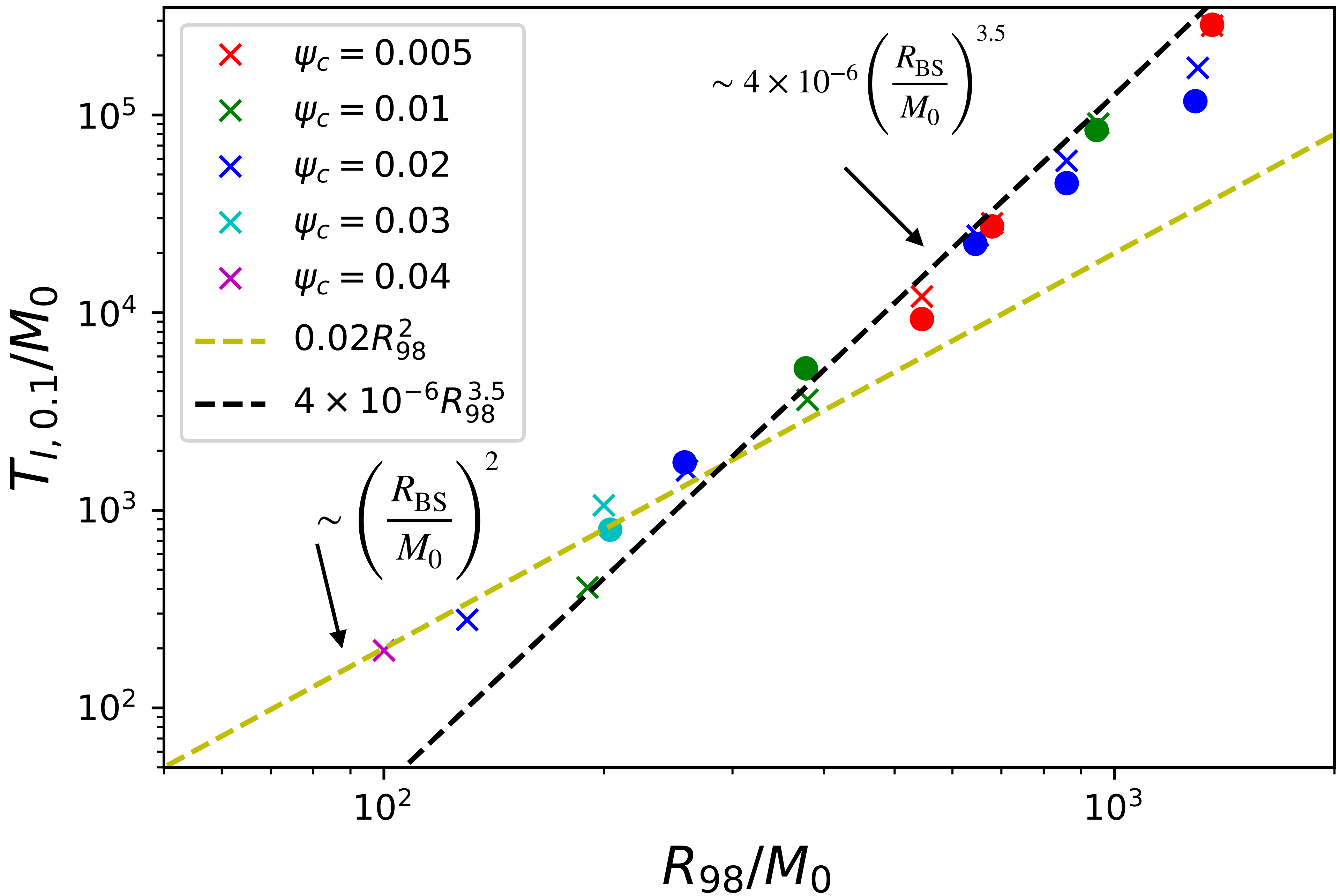
$$\frac{dM}{dt} \simeq 8\pi \times 10^{-2} (\mu M)^2 (\mu M_{\rm BS})^4 \left(1 + \frac{6M}{M_{\rm BS}}\right)$$



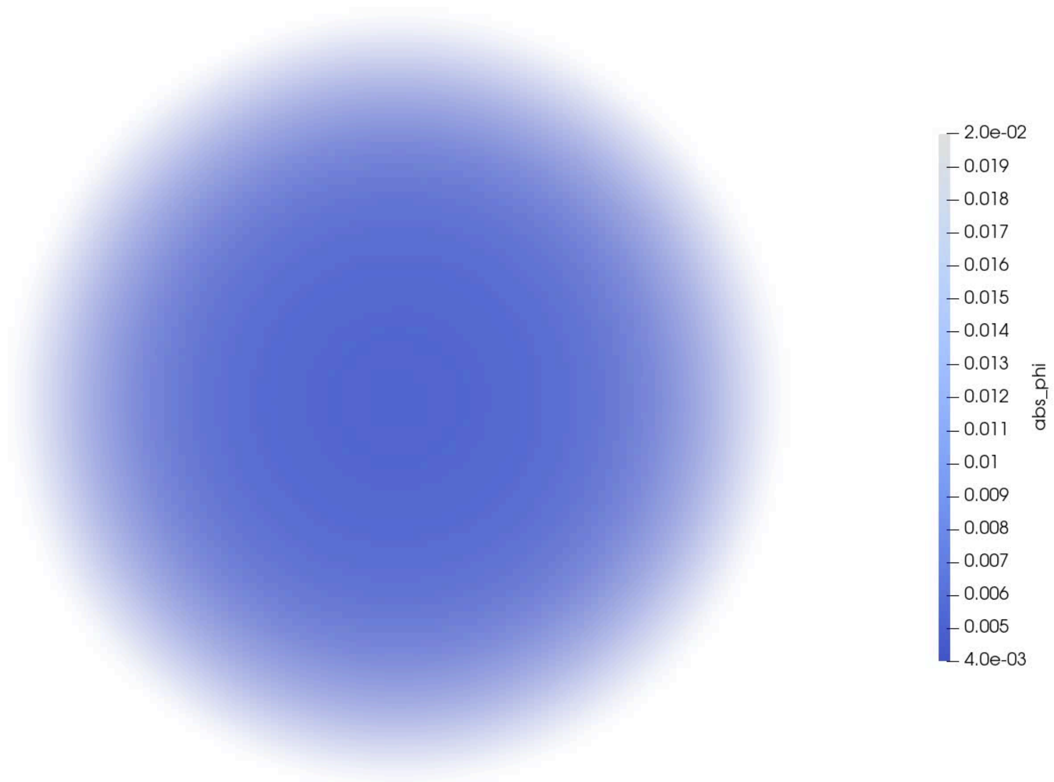
Numerical result

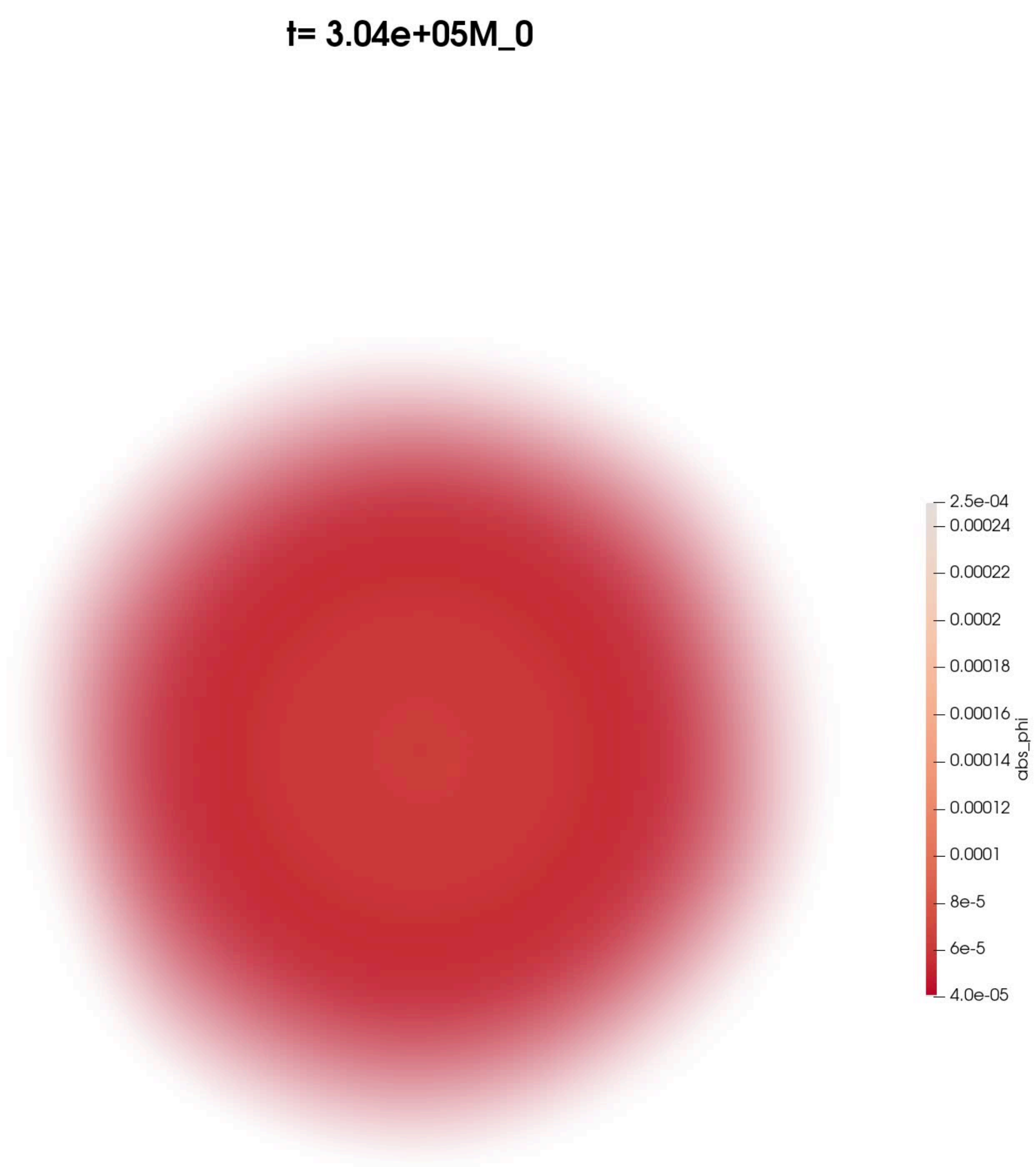
x : numerical simulation
●: from toy model

Time scale of first phase



t= 0.00e+00M_0


2.0e-02
0.019
0.018
0.017
0.016
0.015
0.014
0.013
0.012
0.011
0.01
0.009
0.008
0.007
0.006
0.005
4.0e-03
abs_phi


t= 3.04e+05M_0
2.5e-04
0.00024
0.00022
0.0002
0.00018
0.00016
0.00014
0.00012
0.0001
8e-5
6e-5
4.0e-05
abs_phi

Summary

- Gravitational molecule
  - Spectrum is similar to one of Di-hydrogen molecule.
  - It is typical long-lived state. (also James's talk)
- Accreting BS into BH
  - We observe different stages
    - 1. boson star normal mode
    - 2. castrophic stage
    - 3. gravitational atom
  - We propose toy model describing first phase.
  - This is the formation mechanism of gravitational atom without superradiant instability.


Finish